

Cosmic Ray Production of ${}^6\text{Li}$ by Virialization Shocks in the Early Milky Way

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Abstract

The energy dissipated by virialization shocks during hierarchical structure formation of the Galaxy can exceed that injected by concomitant supernova (SN) explosions. Cosmic rays (CRs) accelerated by such shocks may therefore dominate over SNe in the production of ${}^6\text{Li}$ through $\alpha + \alpha$ fusion without co-producing Be and B. This process can give a more natural account of the observed ${}^6\text{Li}$ abundance in metal-poor stars compared to standard SN CR scenarios. Future searches for correlations between the ${}^6\text{Li}$ abundance and the kinematic properties of halo stars may constitute an important probe of how the Galaxy and its halo formed. Furthermore, ${}^6\text{Li}$ may offer interesting clues to some fundamental but currently unresolved issues in cosmology and structure formation on sub-galactic scales.

Keywords: cosmic rays — Galaxy: formation — Galaxy: halo — Galaxy: kinematics and dynamics — nuclear reactions — nucleosynthesis — stars: abundances

1 Introduction

Apart from ${}^7\text{Li}$, the bulk of the light elements Li, Be and B are believed to arise from nonthermal nuclear reactions induced by cosmic rays (CRs) (Meneguzzi, Audouze & Reeves 1971). In the last decade, extensive observations of LiBeB in population II, metal-poor halo stars (MPHS) have turned up new and unexpected results, spurring controversy as to what type of CR sources and production mechanisms were operating in the halo of the early, forming Galaxy (e.g. Vangioni-Flam, Cassé & Audouze 2000). To date, most models of light element evolution in the early Galaxy have focused on strong shocks driven by supernovae (SNe) as the principal sources of CRs. A general consensus is that Be and B in MPHS mainly originate from the “inverse” spallation process, whereby CR CNO particles are transformed in flight into LiBeB by impinging on ISM H or He atoms (Duncan, Lambert & Lemke 1992). This can be realized if a sizable fraction of the CRs responsible for spallation comprise fresh, CNO-rich SN ejecta (e.g. Vangioni-Flam et al. 2000, Ramaty et al. 2000, Suzuki, Yoshii & Kajino 1999, Suzuki & Yoshii 2001, hereafter SY), as opposed to CRs injected from the average ISM (e.g. Fields & Olive 1999).

The origin of ${}^6\text{Li}$ in MPHS (Hobbs 2000 and references therein) is more mysterious, as current models involving SN CRs face some difficulties. A peculiar aspect of Li is that in addition to spallation, the fusion process of CR α particles with ambient He atoms can be effective, and should actually dominate Li production at low metallicities. (Note that while both ${}^7\text{Li}$ and ${}^6\text{Li}$ are synthesized in comparable amounts, the CR-produced ${}^7\text{Li}$ component is generally overwhelmed by the “Spite plateau” from primordial nucleosynthesis in the metallicity range under consideration; e.g. Ryan et al. 2001.) If the CR energy spectrum is taken to be a standard power-law distribution in momentum (§3), one requires a CR injection efficiency much higher than normally inferred to reproduce the ${}^6\text{Li}$ observations, whether the CR composition is metal-enriched or not (Ramaty et al. 2000; SY, see their fig.2). This raises the question of whether there may have been other sources for ${}^6\text{Li}$.

Suzuki & Inoue (2002; hereafter SI) proposed a new and more natural ${}^6\text{Li}$ production scenario based on a previously unconsidered CR source: CRs accelerated at virialization shocks (VSs), i.e. shocks driven by the gravitational infall and merging of sub-Galactic gas clumps during the hierarchical build-up of structure in the early Galaxy. Such shocks are inevitable consequences in the currently standard theory of hierarchical structure formation (see however §5). We further discuss a number of testable predictions and important implications expected in our scenario for understanding the formation of our Galaxy. The potential relevance to some fundamental issues in cosmology and structure formation on sub-galactic scales is also mentioned.

2 Cosmic Ray Sources in the Early Galaxy

SNe are known to release $E_{\text{SN}} \sim 10^{51}$ erg of kinetic energy in each explosion, driving strong shocks into the ambient medium. These SN shocks are favorable sites for efficient CR acceleration through the first order Fermi mechanism. A plausible value for the injection efficiency ξ_{SN} , i.e. the fraction of the SN kinetic energy imparted to CRs, is 10 – 20%, deduced from comparison of the SN rate and the energy content of CRs currently observed in the Galactic disk. The global energetics of SNe for the early Galactic halo can be estimated from the cosmic star formation history or the total amount of heavy elements ejected by halo SNe (see SI for details of the estimation). Both methods give $\epsilon_{\text{SN}} \sim \mathcal{E}_{\text{SN}} \mu m_p / M_g \simeq 0.15$ keV per particle as the average specific energy input from SNe.

SNe are not the only sources of mechanical energy (and hence CRs through shock acceleration) that may have been active in the early Galaxy. In the framework of the currently successful picture of hierarchical structure formation in the universe, large scale objects are formed through the merging and virialization of smaller subsystems, driven by gravitational forces acting on the dark matter. For each merging hierarchy, shocks should inevitably arise in the associated baryonic gas component, whereby the kinetic en-

ergy of infall is dissipated and the gas heated to the virial temperature of the merged halo (e.g. White & Rees 1978). It is quite plausible that such virialization shocks (VSs) also accelerate CRs (e.g. Miniati et al. 2001).

A guide to how structure formation may have proceeded in our Galaxy, particularly for the Galactic halo, may be offered by the recent numerical simulations of Galaxy formation by Bekki & Chiba (2001, hereafter BC; see also Samland & Gerhard 2003, Abadi et al. 2003). It is expected that sub-Galactic structure eventually merge into a single entity in the central region at redshift $z \sim 2$, whereby the majority of the infall kinetic energy is virialized. The total energy dissipated at this main VS can be evaluated from the virial temperature of the merged system. The virial temperature T_v for a halo of total mass M_t virializing at redshift $z \sim 2$ is $k_B T_v = \mu m_p G M_t / 2 r_v \simeq 0.26 \text{ keV} (M_t / 3 \times 10^{12} M_\odot)^{2/3}$, where r_v is the virial radius, and we have assumed a cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and $h = 0.7$ (see SI). The specific energy dissipated at the VS is thus $\epsilon_{VS} \sim 3 k_B T_v / 2 \simeq 0.4 \text{ keV}$ per particle, higher than the above estimate for SNe by a factor of $\simeq 2.6$, if we adopt $M_t = 3 \times 10^{12} M_\odot$ (Sakamoto, Chiba & Beers 2003). The CR contribution from VSs compared to SNe should similarly be higher, as the CR injection efficiency ξ_{VS} should not be too different from that for SNe (Miniati et al. 2001). CRs accelerated by VSs should therefore be at least as important as SN CRs, and may well dominate at early epochs.

Another, more speculative but potentially interesting possibility is outflows powered by massive black hole(s), which may have been active in the early Galaxy. However, there are numerous ambiguities with such a picture, and here we will concentrate on CRs from VSs and SNe (see SI for more discussion).

3 Model

We employ assumptions and parameters deemed most plausible for the SN CRs. The CR injection efficiency is taken to be $\xi_{SN} = 0.15$ for each SN of kinetic energy $E_{SN} = 10^{51} \text{ erg}$. A standard, single power-law distribution in particle momentum is adopted for the CR spectrum (see SI). The injection spectral index is chosen to be $\gamma_{SN} = 2.1$, appropriate for strong SN shocks, and consistent with the source spectrum inferred for present-day CRs. As assumed in SY, the composition of SN CRs is a mixture of SN ejecta containing freshly synthesized CNO and Fe and the ambient ISM swept up by the SN blastwave.

CRs from VSs are markedly different from SN CRs in a number of important ways. First and foremost, VSs do not synthesize fresh CNO nor Fe, so that the composition of these CRs is completely ascertained by the pre-existing ISM. When the ISM is metal-poor, these shocks induce very little Be or B production through inverse spallation, and are only efficient at spawning Li via $\alpha - \alpha$ fusion. Second, VSs are not necessarily strong ones, particularly for major mergers of systems with comparable masses (Miniati et al. 2001), provided that the pre-shock gas has not cooled significantly. Shock acceleration should then lead to injection indices γ_{VS} steeper than the strong shock limit value of 2, which works in favor of Li production (§4). Major merger

shocks may possess Mach numbers as low as $\simeq 2 - 3$, corresponding to $\gamma_{VS} \simeq 2.5 - 3.3$; $\gamma_{VS} = 3$ is generally chosen below. As with SN CRs, we take the spectral shape to be a momentum power-law distribution and the injection efficiency to be $\xi_{VS} = 0.15$.

A further distinction from SNe is that the VS CR flux should not entail any direct dependence on the metallicity, which is in fact an obstacle to predictive modeling. While the hierarchical growth of structure with respect to cosmic time may be evaluated in concrete ways using e.g. extended Press-Schechter formalisms, relating this to $[\text{Fe}/\text{H}]$ requires additional knowledge of how the combination of star formation, SN nucleosynthesis and chemical evolution in our Galaxy proceeded with cosmic time. This involves large uncertainties, and is not specified in our chemical evolution model. As a first step, we choose to describe the time evolution of VS CRs in a simple, parameterized way, assuming a ‘step function’ behavior: VS CRs begin to be injected from a certain time t_{VS} , maintains a constant flux for a duration τ_{VS} , and then returns to zero. We take the injection duration τ_{VS} to be roughly the dynamical time of the major merger, $\simeq 3 \times 10^8 \text{ yr}$. The injection is also assumed to be uniform, since the effect of the main VS should be global throughout the gas under consideration, unlike SNe. The injected VS CR flux integrated over τ_{VS} is normalized to the above values for ξ_{VS} and ϵ_{VS} . The true evolutionary behavior of VS activity relative to metallicity should actually be probed through future observations of ${}^6\text{Li}$ at low $[\text{Fe}/\text{H}]$ (§4, §5).

After injection by either SNe or VSs, the spectral flux $F_i(E, t)$ for each CR element i evolves with time during subsequent interstellar propagation. This is obtained from time-dependent solutions of the CR transport equation for a leaky box propagation model (SY). Using the transported spectra, we calculate the CR production of LiBeB in the ISM including all three types of reactions: forward spallation of ISM CNO by CR protons and α ’s, inverse spallation of CR CNOs by ISM H and He, and the fusion of CR α ’s with ISM He. For more details, consult SY. We do not consider here the potentially complicating effects of stellar depletion, which are highly uncertain at the moment.

4 Results

For our calculations, we have selected the following sets of parameters for t_{VS} , τ_{VS} and γ_{VS} , respectively, labeled models I - IV: I (0.22, 0.1, 3), II (0.22, 0.1, 2), III (0.32, 0.1, 3), and IV (0.1, 0.5, 3), where t_{VS} and τ_{VS} are in units of Gyr. These were chosen to provide results exemplary of light element production by VS CRs, in contradistinction to that by SN CRs. The evolution of ${}^6\text{Li}$ and Be vs. metallicity calculated for each model until the end of halo chemical evolution ($[\text{Fe}/\text{H}] \simeq -1.5$) is shown in Fig.1, along with the current observational data in MPHS.

We discuss some salient points regarding these results. First, it is confirmed that with our fiducial parameters, production by SN CRs alone (dashed) works very well for the observed Be (and B, not shown), yet falls short of the observed ${}^6\text{Li}$. In contrast, with reasonable values for ϵ_{VS} , ξ_{VS} and γ_{VS} , production by VS CRs is capable of explaining the current ${}^6\text{Li}$ data quite adequately. This mainly owes to two facts: 1) VSs are more energetic than (or at least as ener-

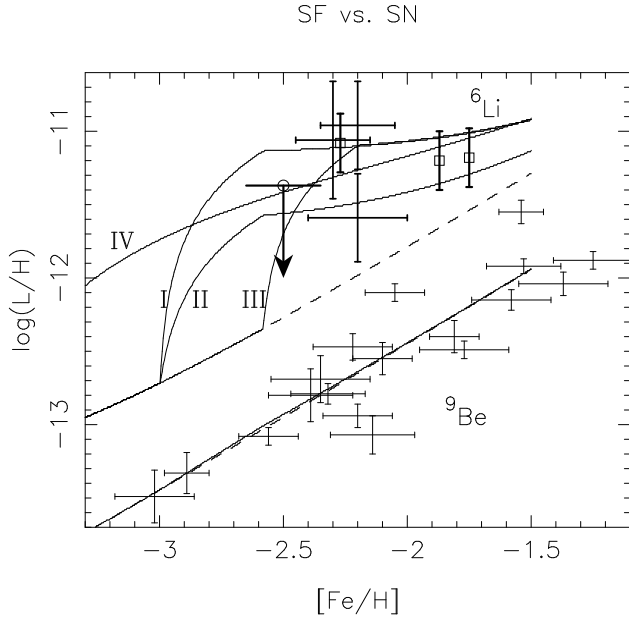


Figure 1: Model results of ${}^6\text{Li}/\text{H}$ (thick) and Be/H (thin) vs. $[\text{Fe}/\text{H}]$, for SN CRs only (dashed curves) and SN plus VS CRs (solid curves), each label corresponding to the parameter set described in the text. Also plotted are current observational data for ${}^6\text{Li}$ (thick crosses from Smith et al. 1998 and Nissen et al. 2000; squares with errors from Asplund et al. 2001; circle with upper limit from Aoki et al. 2003) and Be (thin crosses from Boesgaard et al. 1999).

getic as) SN shocks, as estimated in §2, and 2) VS CRs can generate ${}^6\text{Li}$ at early epochs independently of the metallicity. Regardless of the early evolutionary behavior, identical ${}^6\text{Li}$ abundances are attained at the end of the halo phase for a given γ_{VS} (I, III, & IV), since this is determined by the time-integrated CR flux, for which we had assumed a fixed value. Compared to a flat spectral index of $\gamma_{\text{VS}} = 2$ (II), a steeper one of $\gamma_{\text{VS}} = 3$, more appropriate for low Mach number VS shocks (§3), results in a larger ${}^6\text{Li}$ yield, by about factor of 3. This is because with a constant total CR energy, a steeper index implies a larger CR flux in the sub-relativistic energy range $E \sim 10 - 100$ MeV, where the ${}^6\text{Li}$ production cross section peaks (see fig.1 in SY). Note that a conservatively lower specific energy for VSs, $\epsilon_{\text{VS}} \sim 0.15$ keV/particle (i.e. comparable to SNe), can still be consistent with the available ${}^6\text{Li}$ data provided that $\gamma_{\text{VS}} \simeq 3$.

As already stressed, 2) is a consequence of ${}^6\text{Li}$ synthesis being dominated by $\alpha - \alpha$ fusion, and VSs not creating any new Fe. Depending on the onset time and duration of the VS, the ${}^6\text{Li}$ abundance may potentially reach large values quickly at very low metallicity, which can be followed by a plateau or a very slow rise. On the other hand, SNe unavoidably give forth to freshly synthesized Fe, so a correlation with Fe/H must arise; in fact ${}^6\text{Li}/\text{H}$ vs. Fe/H for SN CRs can never be much flatter than linear (e.g. Ramaty et al. 2000). Moreover, since VSs do not eject fresh CNO, they produce very little Be or B through spallation; only a minuscule contribution can appear as the ISM becomes metal-enriched. This may allow an extremely large

${}^6\text{Li}/\text{Be}$ ratio at low $[\text{Fe}/\text{H}]$. Conversely, we see that SN CRs must play an indispensable role in generating the Be and B observed in MPHS.

Independent of the particular evolutionary parameters, the following abundance trends are characteristic of VS CR production and should serve as distinguishing properties of the scenario for future observations. Going from high to low metallicity: a plateau or a very slow decrease in $\log {}^6\text{Li}/\text{H}$ vs. $[\text{Fe}/\text{H}]$, followed by a steeper decline in some range of $[\text{Fe}/\text{H}]$ corresponding to the main epoch of VS; a steady increase in ${}^6\text{Li}/\text{Be}$, possibly up to values exceeding $\simeq 100$, also followed by a downturn. These traits are very distinctive and not expected in SN CR models, for which the slope of $\log {}^6\text{Li}/\text{H} - [\text{Fe}/\text{H}]$ must be $\simeq 1$ or greater, and the ${}^6\text{Li}/\text{Be}$ ratio constant at sufficiently low $[\text{Fe}/\text{H}]$. Distinction from any production processes in the early universe (e.g. Jedamzik 2000) should also be straightforward, as they predict a true plateau down to the lowest $[\text{Fe}/\text{H}]$, in contrast to an eventual decrease for VS CR models. Further, unique diagnostic features are discussed in §5.

5 ${}^6\text{Li}$ as Fossil Record of Dissipative Processes during Galaxy Formation

A truly unique and intriguing aspect of the VS CR picture is that ${}^6\text{Li}$ in MPHS can be interpreted and utilized as a fossil record of dissipative gas dynamical processes in the early Galaxy. Of particular interest are various correlations expected between the ${}^6\text{Li}$ abundance and the kinematic properties of the stars. On the one hand, ${}^6\text{Li}$ arises as a consequence of gaseous dissipation through gravitationally-driven shocks, and survives to this day as signatures of the dynamical history of hierarchical structure formation in the early Galaxy. On the other, the kinematic characteristics of stars presently observed should reflect the past dynamical state of their parent gas systems, because once stars form, they become collisionless and have long timescales for phase space mixing (e.g. Chiba & Beers 2000). Interesting relationships may then exist among the two observables.

For example, recent intensive studies of the structure and kinematics of MPHS in our Galaxy based on Hipparcos data (Chiba & Beers 2000) have elucidated the detailed characteristics of our Galaxy's halo, such as its two-component nature: an inner halo which is flattened and rotating, and an outer halo which is spherical and non-rotating. This dichotomy has been suggested to result from differences in the physical processes responsible for their formation, dissipative gas dynamics being crucial for the former, and dissipationless stellar dynamics determining the latter. The numerical simulations of Galaxy formation by BC support this conjecture: the outer halo forms through dissipationless merging of small sub-Galactic clumps that have already turned into stars (c.f. Searle & Zinn, 1978), whereas the inner halo mainly forms through dissipative merging and accretion of larger clumps that are still gas rich (c.f. Eggen, Lynden-Bell & Sandage, 1962). In our scenario, ${}^6\text{Li}$ production is a direct outcome of the principal gas dissipation mechanism of gravitational shock heating. If the above inferences on the formation of halo structure are correct, ${}^6\text{Li}$ should be systematically more abundant in stars belonging to the inner halo compared to those of the outer halo, a clearly testable prediction. An important

prospect is that ${}^6\text{Li}$ may provide a quantitative measure of the effectiveness of gas dynamical processes during formation of halo structure, rather than just the qualitative deductions allowed by kinematic studies.

Another possibility regards the main epoch of VS with respect to metallicity (§3). As already mentioned, the relation between ${}^6\text{Li}/\text{H}$ and Fe/H should mirror the time evolution of dissipative energy release through VSs, but is complicated by being convolved with the uncertain ingredients of star formation and chemical evolution. The Fe abundance can be a bad tracer of time, especially at low $[\text{Fe}/\text{H}]$ where the effects of dispersion in SN yields can be extremely large (SY). Stellar kinematics information may offer a handle on this problem. The observed relation between $[\text{Fe}/\text{H}]$ and $\langle V_\phi \rangle$, the mean azimuthal rotation velocity of MPHS, seems to manifest a distinctive kink around $[\text{Fe}/\text{H}] \sim -2$ (Chiba & Beers 2000). Through chemo-dynamical modeling of the early Galaxy, BC have proposed that this kink may correspond to the epoch of the major merger (§3). If this was true, a simple expectation in the context of the VS CR model is that ${}^6\text{Li}/\text{H}$ should be just rising near this value of $[\text{Fe}/\text{H}]$, which is the range occupied by the currently ${}^6\text{Li}$ -detected stars; also expected are a steep decline at lower $[\text{Fe}/\text{H}]$, as well as a plateau or slow rise at higher $[\text{Fe}/\text{H}]$ (i.e. close to model III in fig.1). However, any inferences related to $[\text{Fe}/\text{H}]$ are always subject to the chemical evolution ambiguities. A more reliable and quantitative answer may be achieved by looking for correlations between ${}^6\text{Li}/\text{H}$ and $\langle V_\phi \rangle$ without recourse to $[\text{Fe}/\text{H}]$, as ${}^6\text{Li}$ is a direct and pure indicator of dynamical evolution in the early Galaxy.

Thus the VS CR model for ${}^6\text{Li}$ bears important implications for understanding how our Galaxy formed. If the above mentioned trends are indeed observed, it would not only confirm the virialization shock origin of ${}^6\text{Li}$, but may potentially point to new studies of “ ${}^6\text{Li}$ Galactic archaeology”, whereby extensive observations of ${}^6\text{Li}$ in MPHS coupled with detailed chemo-dynamical models can be exploited as a robust and clear-cut probe of dissipative dynamical processes that were essential for the formation of the Galaxy.

Furthermore, ${}^6\text{Li}$ in Galactic MPHSs may potentially offer interesting clues to a number of outstanding current problems in cosmology and structure formation theory, all involving physics on sub-galactic scales. 1) The global importance of dynamical feedback by SNe has been a long-standing uncertainty in galaxy formation theory (White & Rees 1978, Abadi et al. 2003). Further observations of ${}^6\text{Li}$ vs. Fe or possibly Be and B at low metallicity and comparison with detailed theoretical models may constrain this crucial unknown. 2) The efficiency and location of VSs as commonly assumed on sub-galactic scales has recently been brought into question (Katz et al. 2002, Birnboim & Dekel 2003), with radical implications for how stars and galaxies form and how the galaxy luminosity function is shaped (Binney 2003). The early evolution of ${}^6\text{Li}$ may provide a direct probe of this presently speculative but important suggestion. 3) Comparison of theoretical simulations with observations of dwarf galaxy cores and of satellite galaxies of our Galaxy and within the Local Group indicate that standard cold dark matter (CDM) produces much more substructure than is actually seen. This “CDM crisis” may point to non-standard dark matter properties, such as warm

dark matter, self-interacting dark matter or even more exotic proposals (e.g. Ostriker & Steinhardt 2003, Madau & Kuhlen 2003). On the other hand, the apparent discrepancy may be the result of strong feedback by SNe or a UV background. These different possibilities should result in differences in the early evolution of ${}^6\text{Li}$, potentially constituting a unique probe. 4) From a combined analysis of measurements of cosmic microwave background anisotropies by *WMAP* and of the power spectrum on galactic and subgalactic scales, it has been suggested that the spectrum of primordial density fluctuations deviates from a standard, single power-law (Spergel et al. 2003). Although less drastic than non-standard dark matter, this would also modify the growth of structure on subgalactic scales (Madau & Kuhlen 2003), and the consequent ${}^6\text{Li}$ production at early epochs. More detailed investigations of these intriguing prospects are certainly necessary, but in principle, ${}^6\text{Li}$ in our Galactic halo may shed light on these issues of paramount importance for cosmology and the physics of the early Universe.

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